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APPLICATIONS OF DIGITAL IMAGE PROCESSING IN TESTING AND EVALUATION OF COMPOSITE MATERIALS

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May 1990

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MTL TR 90-24	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) APPLICATIONS OF DIGITAL IMAGE PROCESSING IN TESTING AND EVALUATION OF COMPOSITE MATERIALS		5. TYPE OF REPORT & PERIOD COVERED Final Report
7. AUTHOR(s) Gary L. Hagnauer, James D. Kleinmeyer, John J. Wixted,* and John H. Grubbs*		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Materials Technology Laboratory Watertown, Massachusetts 02172-0001 SLCMT-EMP		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1L162105.AH84
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Laboratory Command 2800 Powder Mill Road Adelphi, Maryland 20783-1145		12. REPORT DATE May 1990
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 16
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES *Department of the Army - U.S. Military Academy, Department of Civil and Mechanical Engineering, West Point, New York 10996-1695		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Digital image analysis . Environmental durability. Materials evaluation . Vision system Composites Mechanical testing Helicopter blades, Nondestructive testing		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (SEE REVERSE SIDE)		

Block No. 20

ABSTRACT

✓ This report describes the development and application of digital image processing techniques for analyzing the fracture behavior and environmental deterioration of test specimens prepared from composite laminate materials used in the manufacture of helicopter rotor blades. The digitized images were evaluated using pixel histograms generated through routines developed on a C-interpreter. Laminate fiber orientation and aging conditions were found to have a significant effect on the observed fracture patterns and surface characteristics of the test specimens. Pixel histograms of environmentally aged test specimens were broader and shifted to higher grey level values compared to histograms of the unaged specimens. Under the test procedures developed, digital image analysis results were reproducible and fiber orientation did not significantly affect the average grey level of either aged or unaged specimens.

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INTRODUCTION

In a collaborative project with the United States Military Academy, the U.S. Army Materials Technology Laboratory (MTL) is currently implementing state-of-the-art robotics and digital image processing to fully automate the mechanical testing of composite materials. This report describes the development and application of digital image analysis (DIA) techniques for analyzing the fracture behavior and environmental deterioration of test specimens prepared from composite laminate materials used in the manufacture of helicopter rotor blades. The primary objective was to determine if image processing could provide reliable qualitative (visual) information on the fracture characteristics of specimens subjected to flexural (three-point loading) testing. A secondary goal was to ascertain whether DIA techniques could be usefully employed to investigate the effects of moisture and temperature on the environmental aging of composite materials. Image processing technology is briefly reviewed in the Image Processing Techniques Section. The automated mechanical testing and digital image processing systems are described in the Automated Mechanical Testing System and the Digital Imaging Processing System Sections. Details relating to the fabrication of specimens, treatment, and conditioning of specimens and procedures used for testing are presented in the Test Specimens and Testing Procedures Section. Test results, conclusions, and recommendations for further development are considered in the remaining sections of this report.

IMAGE PROCESSING TECHNIQUES

In general, an image processor works by digitizing an incoming analog signal sent from a camera. An incoming image is divided into a grid of "pixels" (picture elements) displayed as the image on a monitor. Each pixel has a value in memory ranging from zero to 255 corresponding to 256 shades of grey and exists in an array location corresponding to its position in the image. Contrast plays an important role in image processing since the sharper the contrast achieved, the greater the variation in the resulting pixel values. A critical factor in achieving good contrast is the lighting used. The image processor analyzes pixel values and manipulates images by changing the pixel values. These manipulations can take several forms: digital filtering, lookup table manipulation, and logical operation.

Digital Filtering

Digital filtering provides an effective method for the manipulation of images through the modification of each pixel relative to its neighbor. One such implementation of digital filtering is through the use of 2-dimensional convolution. This mathematical method is used to calculate a weighted average of each pixel based on the intensities of its neighbors. The digital filter is implemented by convolving the image matrix with a "kernel" matrix which is specified prior to the operation. The kernel is responsible for defining the coefficients needed to implement the desired filter.¹ For example, a 3 x 3 matrix kernel may be convoluted with the image matrix

$$\begin{matrix} 0 & 0 & 0 \end{matrix}$$
$$\begin{matrix} 0 & X & 0 \end{matrix}$$
$$\begin{matrix} 0 & 0 & 0 \end{matrix}$$

1. JAIN, A. K. Fundamentals of Digital Image Processing. Prentice Hall, Englewood Cliffs, NJ, 1989.

where X is the target pixel and 0 is a pixel in an adjacent screen position. The filter action is dependent upon specification of the kernel coefficients. Different filtering techniques are used to produce specific results. For example, the matrix

$$\begin{array}{ccc} -1 & -1 & -1 \\ -1 & +9 & -1 \\ -1 & -1 & -1 \end{array}$$

is used as a typical "high-pass" filter. This produces greater clarity and detail in the resulting image. Conversely, the matrix

$$\begin{array}{ccc} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{array}$$

functions as a "low-pass" filter which tends to blur details giving a better general outline of objects within the image. This is extremely useful for artificial intelligence applications which use object recognition.

In principle, an image processor is capable of handling any size matrix. Rectangular matrices, for example, are used for vertical and horizontal edge detection. Matrix convolution, however, requires many calculations; whereas the larger the kernel, the longer the filtering takes. A faster means of image manipulation relying on specific hardware within the system is often desirable for more efficient image analysis.

Lookup Tables

Lookup Tables, referred to as LUTs, are hardware mechanisms used to manipulate pixel values. Data can be passed through LUTs, which significantly accelerate the manipulative process. LUT operations are programmed to allow for flexibility in specifying their operation. Unlike digital filtering, LUTs affect only the target pixel without regard to its neighbors; it is limited to changing pixel values by constant increments. The programming capability allows the increment to vary depending upon a pixel's original value. For example, an LUT may be programmed to invert an image. The image data is passed through the LUT and grey level values are inverted to give a negative image; i.e., zero values become 255, one becomes 254, etc. Since an image system may have as many as 24 LUTs, the flexibility in using these registers is immense. LUTs can be programmed to set all but a limited range of values to zero, causing all values within a range to be set equal, or any combination of a number of LUT operations can be performed simultaneously using multiple LUTs.

Logical Operation

As mentioned previously, space is reserved in memory for as many as 24 LUTs to be present at one time. Likewise, space is reserved in memory for four different frame buffers, each having four image registers. Image registers are used to display the image on the monitor. By calling the frame buffer and register, the stored image is displayed. Multiple image registers allow, not only for multiple images to be stored and viewed, but also provide

the means for the use of logical operations. By applying the logical functions, images can be used to affect other images. In applying subtraction or addition, for example, features may be added or subtracted from the target image. The image registers can also display live data; a standard backdrop can be subtracted from the live image to allow for motion detection. Image registers do not modify pixel values. They are used instead as the storage location for the pixel values of the image they are to display. Multiple registers, however, can be used to create new images from two or more registers.

AUTOMATED MECHANICAL TESTING SYSTEM

An automated work cell has been developed for mechanical testing. The work cell includes an Instron Universal Testing Instrument (Instron Corporation, Canton, MA), a Zymate robot arm and controller (Zymark Corporation, Hopkinton, MA), specimen racks, a bar code reader, and an IBM PC/AT. The Instron Tester is a heavy duty instrument (Model 4206) with hydraulic grippers and load cells selected especially for tensile and flexural testing of polymer matrix composite materials. The robot was programmed to automatically transfer test specimens from specimen racks to the test apparatus and then remove specimens from the apparatus after the test is completed. All data acquisition, handling, and reporting are also fully automated. The ASTM D 790 Test Method for three-point loading was used to determine the flexural properties of test specimens in this study.² Stress was applied to fracture the specimens; however, the strain was limited to prevent specimens from breaking apart. The flexural test specimens were 1.45 mm thick by 19.3 mm wide and greater than 10 cm long. The support span for the three-point loading test was 25.4 mm. To handle flexural test specimens for this study, the robot end-effector and test procedure required modification. Originally, the grippers were designed to handle samples having a width of 14 mm or less. Also, in the original procedure the robot gripped the specimen at its mid-point and loaded it in the center of the test fixture between the two supporting beams. Since the robot grippers needed at least 30 mm between the supports to place the specimen in the test fixture and the support span distance was only 25.4 mm wide, the procedure had to be changed. To prevent slippage and allow for wider specimens, the standard grippers were replaced with rubber padded grippers. The procedure was modified in two ways: First, the robot was instructed to grip the specimen at one end (instead of the center) and to place the specimen on the support beams so that the specimen was centered. Second, a new routine was added to refine specimen placement and insure that the sample was perpendicular to the end supports. With the above modifications, the robot could now manipulate test specimens in a uniform manner. This was important, not only to insure accurate testing, but also to guarantee that specimen failure occurred in the same region for each specimen in order to standardize the image analysis. Hence, automation reduced labor costs and provided more accurate and precise test results by insuring that test procedures were rigidly followed and specimens were exactly placed in test fixtures.

DIGITAL IMAGING PROCESSING SYSTEM

The original hardware configuration of the vision system consisted of a Panasonic VHS portable video camera coupled with a Series 151 Image Processor (Imaging Technology, Woburn, MA) and a Zenith PC. The primary hardware considerations in capturing a good image were lighting and the performance characteristics of the camera. Due to problems with

2. ASTM D 790 in *Annual Book of ASTM Standards*, 08.01. American Society for Testing and Materials, Philadelphia, PA, 1987.

focal length, the VHS camcorder was eventually replaced with a 12.5 mm CCD camera. The digital image processing system is illustrated in Figures 1 and 2. Specimens fabricated for flexural testing were examined (see the Test Specimens and Testing Procedures Section).

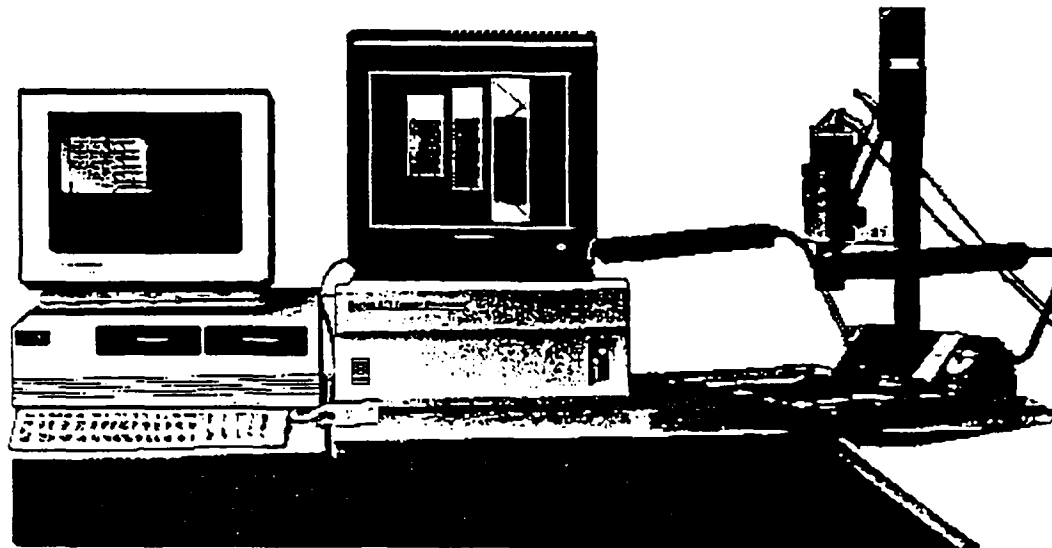


Figure 1. Digital image processing system.

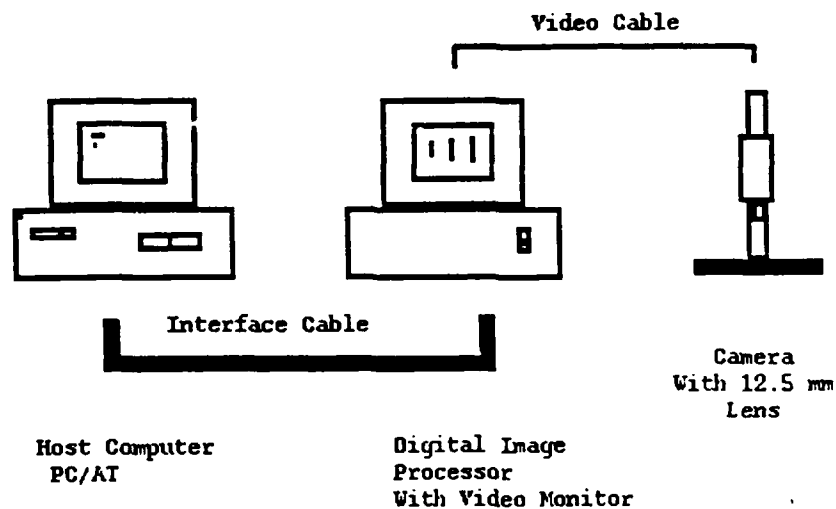


Figure 2. Digital image processing system.

Lighting

Several variations in lighting specimens for image analysis were investigated. Initially, fluorescent room lighting was attempted due to its convenience. Although the unbroken specimens could use this type of lighting, the light was not direct enough to illuminate the fractured region of a failed specimen. Next, a 60 watt incandescent light bulb in a portable socket was added to the setup. By adjusting the position of the light, good images could be

obtained; however, there were problems in uniformity and standardization. The VHS camera had to be mounted on a tripod for stability due to its size. In order to focus the camera on the entire specimen, the specimen had to be placed perpendicular to the plane of the camera. Various angles of incidence for the lighting were tried, but it was determined that the 60 watt bulb was too dim to provide good contrast. If the light was placed too far from a specimen, it had too little effect; whereas when placed closer, the angle of incident would cause shadows on the specimen. Assuming that a brighter light from a further distance might prove more effective, a high intensity quartz halogen studio light was substituted for the 60 watt bulb. Although the quartz light greatly improved contrast and did not produce the distinct shadows, it too had faults. Since the test specimens were deformed and no longer perfectly flat following flexural testing, light from the quartz halogen light reflected differently off the two planes formed by the fractured specimens. The difference in the reflection was readily apparent in the image because the light was so intense. Hence, any attempt at image analysis was inherently skewed because specimen regions with the same properties would register as having different pixel values. At this point, backlighting was evaluated. Since the specimens were translucent, light could be filtered through them. Fractured regions appeared to be darker than unaffected regions. Backlighting, however, did not sharply define the fractured regions. Fractured and unfractured areas tended to fade into one another. In order to quantitatively analyze fractured regions, greater contrast was needed. Therefore, it was decided to continue using surface lighting. Clearly, a compromise to the lighting problem had to be found. The light needed to be bright and yet not direct, and fractured regions of specimens needed to be distinctly shown. The apparatus finally chosen for lighting was a light table originally used for making 35 mm slides. It was equipped with a camera mount and two eight-inch white fluorescent adjustable lamps stationed opposite each other. The fluorescent lighting provided the indirect brightness that was needed for accurate image acquisition and shadows were no longer a problem. The apparatus was sufficiently flexible and yet rigid in construction so that once suitable settings were found, the lighting and camera could be locked into position to assure reliable operation.

Camera Focal Length

Several problems were encountered in using the VHS portable camera. First, the focal length of the camera was too large to permit focused, close-up imaging of test specimens at a distance less than three feet. While image recording was not hampered by this requirement, a shorter focal length camera would take up far less space in an automated procedure. The VHS camera also had an automatic white balance as a built-in feature. Although this feature is good for standard filming, in this application the white balance would often compensate for or filter out the contrast trying to be attained. Finally, the VHS camera did not meet the requirement for automation; i.e., the camera must be mounted in a standard position and not moved to capture larger or smaller images. To solve the above problems, the VHS camera was replaced with a compact 12.5 mm CCD camera. The 12.5 mm lens allowed the camera to be located on the light table directly above the sample. Furthermore, the CCD camera had a variable aperture which allowed the amount of light the camera registered to be adjusted manually. The small size of the camera and relative low cost compared to the VHS recorder made it ideal for automated image analysis.

Software Considerations

The Imaging Technology Series 151 Image Processor is designed to be programmed in the C programming language. Interpreter software included with the system was used to establish

routines for isolating fractured regions of test specimens, filter out visibly unaffected regions, and determine specimen damage either in square inches or as a percentage of the fractured region. Recognizing that the location of the fracture damage region is well defined by the flexural test procedure, image acquisition and analysis were generally limited to a 19 mm region surrounding the area of probable damage. Methods used to capture and manipulate images were discussed in the Image Processing Techniques Section. A function known as histogram equalization was used to enhance the contrast of the damaged regions in test specimens. Realizing that the image consists of 256 shades of grey, it was expected that most shades would fall away from the very dark (black) regions and the very light (white) regions. The damage regions, in fact, were only a slightly lighter shade of grey than the undamaged regions. The histogram equalization function equalizes the brightness of the entire image based upon the area of interest. It then uses LUTs to force a bimodal distribution onto the area specified. This has the effect of greatly enhancing the contrast of the area of interest. Whereas an image initially may be composed of many shades of grey, difficult for the eye to discern, application of histogram equalization scales the ranges of values in the area of interest across the entire spectrum. This makes filtering out ranges of values far simpler. LUTs were utilized for filtering to decrease analysis time and simplify operation. A stretch frame function was used to finalize the area to be calculated. Similar to the histogram equalization function, the stretch frame function forces a distribution of grey levels onto a range of values. Specifically, the range of grey values from 150 to 175 was chosen for this application. All values below 150 were turned to zero (black) and any value above 175 was equated to 255 (white). Those values in the narrowly specified range were then transformed to fit a normal distribution. In effect, a large number of black and a large number of white values were obtained. As the number of pixels in the range of 150 to 175 were small compared to the total number, very few nonblack or nonwhite values were obtained. After histogram equalization, values representing fractured regions became lighter, while those unaffected became darker. The stretch frame made the contrast even sharper, by turning the fractured region white and the unfractured region black. The only part of the image remaining was the fracture region which appeared on the monitor as sharp white in a field of black. Finding the extent of damage in the fractured region was relatively simple. All white pixels were physically counted using the histogram function to create a 256 x 2 array. Image analysis of a one-inch square piece of white paper was performed to determine the standard number of pixels per square inch, keeping experimental conditions constant. The fraction or percentage damage could then be directly calculated from the number of white pixels.

TEST SPECIMENS AND TESTING PROCEDURES

The laminates used in this study were prepared from unidirectional S2-glass fiber, SP250 epoxy resin prepreg materials (3M Corporation). The SP250 resin is a 250°F cure system consisting of a mixture of diglycidyl ether of bisphenol A (DGEBA) and epoxy cresol novolac (ECN) epoxies cured with dicyandiamide and using 3-(p-chlorophenyl)-1,1-dimethylurea as an accelerator. The laminates were fabricated by layering six plies of prepreg (lamina) in four different layup configurations. Defining lamina orientation as the angle (degrees) between the prepreg fiber direction and a reference axis (the X-axis, or flexural test specimen long axis, which is perpendicular to the load exerted during the three-point bend test), the laminates are designated:

0°	fiber orientation	[0 ₆]T
60°	" "	[60 ₆]T
±45°	" "	[+45 ₂ -45 ₂ +45 ₂]T
0/90°	" "	[90 ₂ 0 ₂ 90 ₂]T

The cure cycle for the laminates involved a 35 minute hold at 165°F followed by two hours at 250°F. Flexural test specimens (nominally, 100 mm long x 19.3 mm wide x 1.45 mm thick) were carefully machined from the laminate materials and conditioned by drying at 60° under vacuum for five days.

Test specimens were immersed in distilled water at 80°C for 144 hours to accelerate environmental aging. The percentage of moisture uptake was determined by measuring the change in specimen weight before and after immersion. Upon cooling to room temperature, wet specimens were blotted with filter paper and immediately weighed. After immersion and weighing, the specimens were dried under vacuum at 60°C for at least five days or until all traces of moisture were removed. The conditioned specimens were then stored in a desiccator. As mentioned in the Automated Mechanical Testing System Section, the ASTM D 790 method and an Instron Series IX Automated Materials Testing System with 4200 Series interface was used for three-point loading flexural testing. A support span of 25.4 mm (one inch) was chosen because of the specimen thickness. The crosshead speed and temperature were 0.100 in./min and 25°C, respectively. Flexural modulus, flexural strength, and the maximum load at yield were determined. The test system for image analysis and software for analyzing specimen fracture damage were described in the Digital Image Processing System Section. Although not implemented in this study, the system was designed for robotic placement of specimens. Exact placement of specimens, control of lighting, and camera position is essential to obtain reproducible results. Pixel histograms, plots of pixel count versus grey level value, were particularly useful in discerning changes in images due to the accelerated environmental aging of specimens. To obtain reproducible results, the test specimens had to be completely dry. The total image analysis time for each specimen was about two minutes.

RESULTS AND DISCUSSION

Flexural test results for conditioned (dry) laminate specimens before and after accelerated aging are summarized in Table 1. In general, immersion of test specimens in water at 80°C for 144 hours caused a reduction of 10% to 30% in their flexural properties. As expected, fiber orientation has a significant effect on mechanical properties. However, laminate layup apparently does not effect the relative change in flexural properties with accelerated environmental aging. Five to ten years exposure under tropical rain forest conditions are required to produce similar relative changes in the mechanical properties of this material.³

3. SACHER, R. E., and DOHERTY, J. *Long Term (5-13 Years) Weathering Analysis of Glass Reinforced Epoxy Composites* in Proc. 1985 Tri-Service Conference on Corrosion. Orlando, FL, December 1985, p. 189-295.

Table 1. ASTM D 790 FLEXURAL TEST - SP250 LAMINATES

	Specimen	Modulus (MPa)	Strength (MPa)	Max. Load (kN)
0°	Control	32,800	1,440	1.69
	Aged (144 h)	29,700	1,046	1.36
60°	Control	14,700	376	0.475
	Aged (144 h)	10,200	345	0.461
45°	Control	7,323	299	0.339
	Aged (144 h)	5,292	240	0.303
0/90°	Control	1,520	280	0.294
	Aged (144 h)	1,169	211	0.253

Photographs of fractured test specimen images as displayed on the image monitor are shown in Figure 3. Fracture regions are barely visible in the upper photograph of the actual, unprocessed images. However, by applying image processing routines, as described in the Digital Image Processing System Section, the fracture regions become readily apparent. As shown in the lower photograph, the unfractured regions are totally black and each specimen has a distinctive fracture pattern. The fracture direction parallels the lamina fiber orientation direction and the fracture patterns are highly reproducible. The damage mode in the unaged specimens is a combination of delamination and fiber separation within plies. Pixel analysis of white/grey versus black regions shows that the percentage white/grey pixels (apparent percent damage) is greatest for the 0° specimen and least for the 60° specimen (Table 2).

Table 2. DAMAGE AREA, MEAN GREY LEVEL VALUES, AND PERCENTAGE MOISTURE UPTAKE

Specimen	Average Grey Values		Moisture Uptake (weight-%)	Apparent % Damage (Unaged Specimens)
	Control	Aged		
0°	160.5	191.0	2.82	90
60°	161.9	188.7	2.90	13
+45°	161.1	189.4	2.98	38
0/90°	161.9	188.7	2.70	20

Test specimens immersed in water at 30°C for 144 hours were found to have similar percentages moisture uptake. Thus, fiber orientation does not seem to affect moisture absorption. This is consistent with the fact that water absorption is a matrix dominated property and infers that, except for fiber orientation, resin-fiber interface characteristics of the specimens are essentially identical.

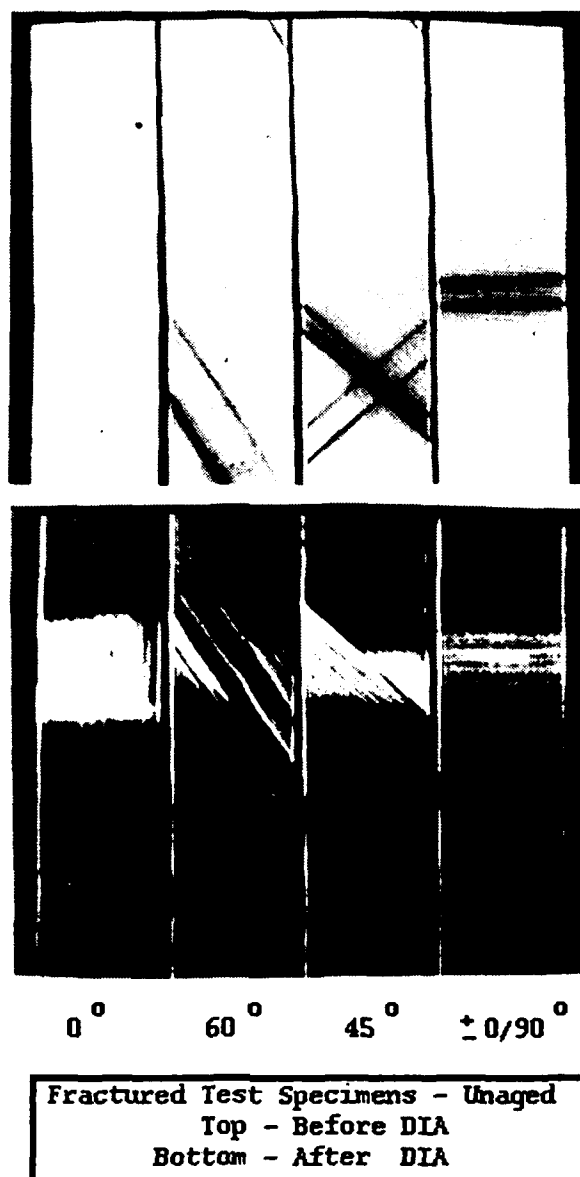


Figure 3. Fractured test specimen - control (unaged). Top - before image processing. Bottom - after image processing.

Image analysis was performed after the aged specimens were conditioned (dried at 60°C) and fractured. Photographs of the fractured, "aged" specimens taken from the image monitor are shown in Figure 4. Fracture regions are hardly discernable in either set of images before or after DIA. However, comparing the images of the control (unaged) and aged specimens after DIA, a remarkable difference is evident. The unfractured regions of the aged specimens are no longer black. Fiber orientation is clearly evident in the unfractured regions of the aged specimens. Indeed, pixel histograms (Figure 5) show that the pixel count distribution of aged specimens is shifted to higher grey level values (white pixel value = 255) with respect to grey level values of the controls. The calculated mean weighted average grey level for control and aged (144 h) specimens are listed in Table 2. The average grey level values for the control specimens are 160.5 to 161.9, compared with 188.7 to 191.0 for the aged specimens.



FRACTURED TEST SPECIMENS - AGED
 TOP - BEFORE DIA
 BOTTOM - AFTER DIA

Figure 4. Fractured test specimens - aged. Top - before image processing. Bottom - after image processing.

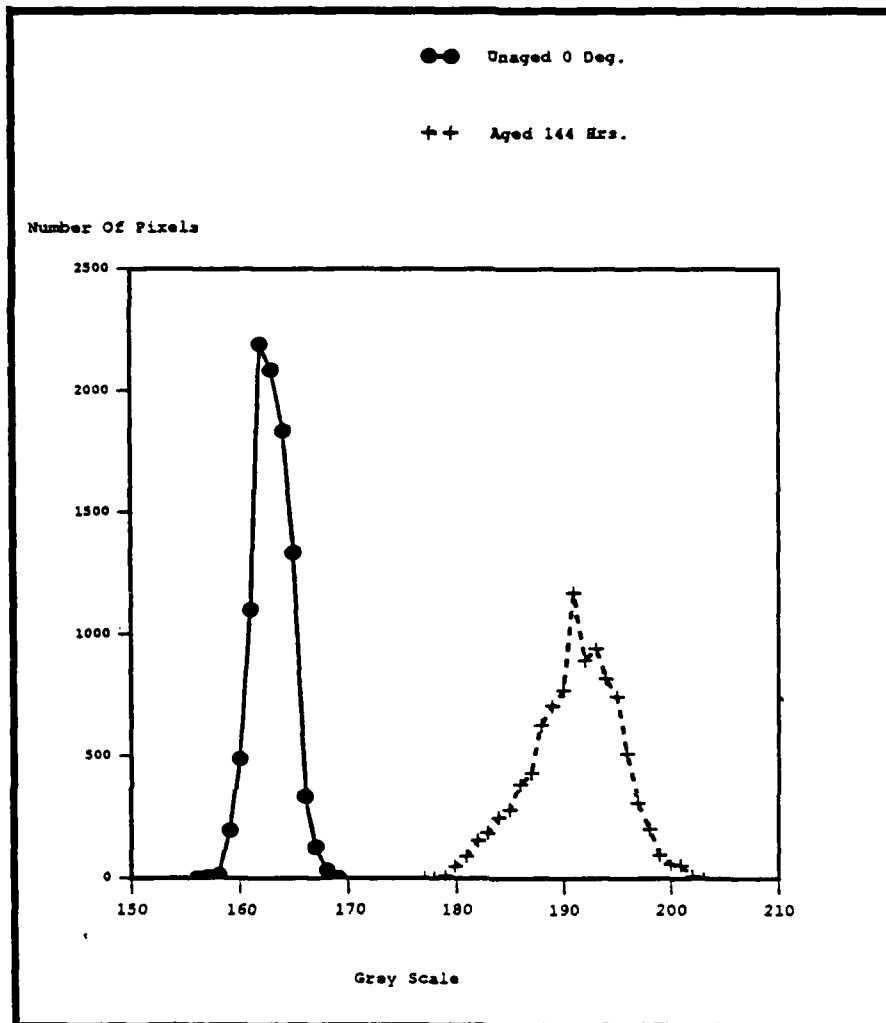


Figure 5. Pixel histograms - DIA 0° fiber orientation test specimens. Control (unaged). Aged (immersed 144 hours at 80°C).

Insuring that image processing conditions and test procedures remain constant was essential for obtaining reproducible DIA results. The DIA of wet specimens was very sensitive to the time interval between sampling and imaging and did not show the large shift in grey level values observed for aged specimens that were conditioned (dried). Excellent reproducibility was obtained when specimens were conditioned and maintained in the dry state. DIA of conditioned specimens aged under identical conditions and stored in a desiccator generated similar pixel histograms (Figure 6). Fiber orientation, relative to the camera position, however, did not significantly affect the average grey level values of aged and unaged specimens. Specimens could be rotated 90° for image analysis with little effect on pixel count distribution under the prescribed test conditions.

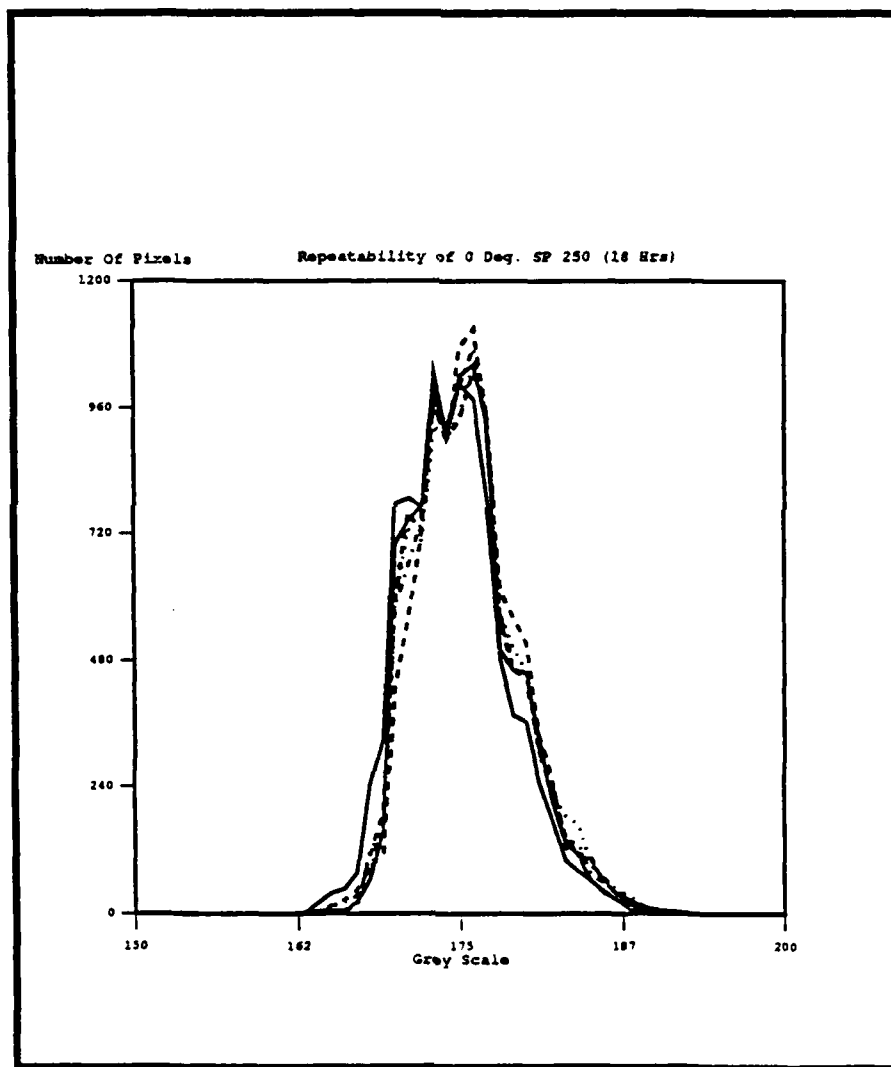


Figure 6. Pixel histograms - DIA 0° fiber orientation test specimen.

CONCLUSIONS AND RECOMMENDATIONS

Digital image processing technology was employed to capture and analyze images of fractured aged and unaged, composite test specimens. The digitized images were evaluated using pixel histograms generated through routines developed on a C-interpretter. Laminate fiber orientation and aging conditions were found to have a significant effect on the observed fracture patterns and surface characteristics of the test specimens. Pixel histograms of environmentally aged test specimens were broader and shifted to higher grey level values compared to histograms of the unaged specimens. Under the test procedures developed, DIA results were reproducible and fiber orientation did not significantly affect the average grey level values of either aged or unaged specimens. Digital image processing is a promising technique for investigating the fracture and aging behavior of glass fiber-reinforced (epoxy resin matrix), composite materials. Digital image processing can provide reliable and quantitative information relating to visual changes induced in composite test specimens due to accelerated environmental aging. Additional studies are required to improve analytical procedures for describing and quantifying fracture characteristics of flexural test specimens and to understand how and why environmental aging affects changes in pixel histograms. A detailed, systematic study to determine possible correlations between DIA and results obtained from mechanical, physical, and chemical characterization of composite test specimens as a function of environmental aging conditions is needed. Finally, possible applications of this technology to other types of composites, plastics, rubbers, coatings, and adhesives should be investigated.

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IN TESTING AND EVALUATION OF COMPOSITE
MATERIALS - Gary L. Hagnauer, James D. Kleinmeyer,
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